Lepton Dipole Moments

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LNF, XIX Spring School “Bruno Touschek”, 7 May 2018

Lepton dipole moments: a conceptual challenge

The Dim-4 SM provides an accidental flavour symmetry:

- it holds in QCD and EM interactions;
- in the quark sector, it's broken by EW interactions.

The lepton sector strictly conserves flavour and CP.

At the same time, we have remarkable phenomenological evidences of FV in the neutrino sector, but...

...No evidence of lepton CP violation and of:

- $l_h^\pm \to \gamma + l_i^\pm$ where $h, i = e, \mu, \tau$,
- $l_h^\pm \to l_i^\pm l_j^\pm l_k^\mp$ where $h, i, j, k = e, \mu, \tau$,
- $Z \to l_h^\pm l_i^\mp$ where $h, i = e, \mu, \tau$,
- $H \to l_h^\pm l_i^\mp$ where $h, i = e, \mu, \tau$.

Lepton flavour and CP violation *are* new physics

Leptons come in three generations and mix: CPV is expected.

Neutral sector: neutrino mass generation mechanism

ν oscillation *is* a BSM signal, but what is the underlying picture?

Charged sector: lepton flavour and CP puzzle

cLFV & CPV are severely constrained, why BSM is so elusive?

The handhold: leptonic electric dipole moment

"The KM phase in the quark sector can induce a lepton EDM via a diagram with a closed quark loop, but a non-vanishing result appears first at the four-loop level and therefore is even more suppressed, below the level of

$$d_e^{\rm CKM} \leq 10^{-38} e\ \text{cm},$$

and so small that the EDMs of paramagnetic atoms and molecules would be induced more efficiently by e.g. Schiff moments and other CP-odd nuclear momenta. [...] The electron EDM is not the best way to probe CP violation in the lepton sector.

M. Pospelov and A. Ritz, Annals Phys. **318** (2005) 119

A selection of limits on leptonic observables

Lepton EDMs:

- $d_e < 0.87 \times 10^{-28} e$cm at the 90% C.L.
  ACME Collaboration, Science **343** (2014) 269;
- $d_\mu < (-0.1 \pm 0.9) \times 10^{-19} e$cm at the 90% C.L.
  Muon $(g-2)$ Collaboration, Phys. Rev. D **80** (2009) 052008;
- $-0.22 \times 10^{-16} e$cm$< d_\tau < 0.45 \times 10^{-16} e$cm at the 95% C.L.
  Belle Collaboration, Phys. Lett. B **551** (2003) 16.

cLFV in the muon sector, the “golden” channels:

- BR$(\mu \to 3e)< 1.0 \times 10^{-12}$ at the 90% C.L.
  SINDRUM collaboration, Nucl. Phys. B **299** (1988) 1;
- $\sigma(\mu^- \to e^-)/\sigma(capt.)\big|_{\rm Au} < 7.0 \times 10^{-13}$ at the 90% C.L.
  SINDRUM II collaboration, Eur. Phys. J. C **47** (2006) 337;
- BR$(\mu \to \gamma + e)< 4.2 \times 10^{-13}$ at the 90% C.L.
  MEG collaboration, Eur. Phys. J. C **76** (2016) 434;

Recent developments

One can contribute in two ways:

1. performing precise calculations for backgrounds;
2. interpreting properly the current absence of signals.

1) Typical low-energy cLFV background computations:

- radiative decays, $l_1 \to l_2 + \gamma + 2\nu$;
- rare decays, $l_1 \to 3l_2 + 2\nu$, $l_1 \to 2l_2 + l_3 + 2\nu$.

2) Typical interpretive approaches:

- bottom-up, effective field theoretical formulations;
- top-down, UV-complete extensions of the SM.

Precise calculations for cLFV backgrounds

Leptonic radiative and rare decays are known at the Next-to-leading order in the Fermi Theory.

- $l_1 \to l_2 + \gamma + 2\nu$

  M. Fael, L. Mercolli and M. Passera, JHEP **07** (2015) 153

  GMP, A. Signer and Y. Ulrich, Phys. Lett. B **772** (2017) 452

- $l_1 \to 3l_2 + 2\nu$

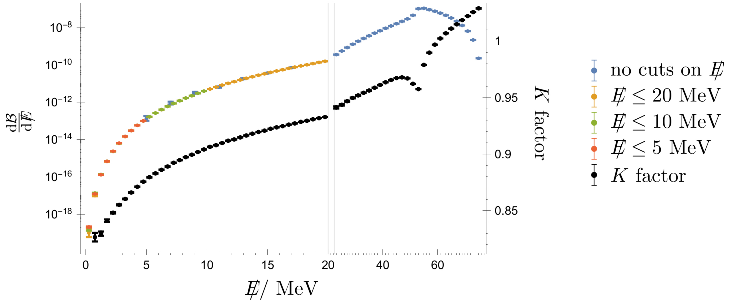
  M. Fael, C. Greub, JHEP **1701**, 084 (2017)

  GMP, A. Signer and Y. Ulrich, Phys. Lett. B **765** (2017) 280

Fully differential NLO Monte Carlo for the radiative/rare decays of a polarised lepton is now available.

Predictions can be tailored on future experiments, arbitrary kinematic cuts can be implemented!

Rare decay at the NLO: the outcome



The differential decay distribution w.r.t. the invisible $\not{E}$ at NLO in blue, orange, green and red (see text) and the K factor NLO/LO in black. To emphasize the low energy tail, the scaling is broken at $\not{E} = 20$ MeV. The error bars indicate the numerical error of the Monte Carlo integration.

There are substantially fewer background events than expected from the naive tree-level simulations.

Standard Model Effective Field Theory

Assumptions: SM is merely an effective theory, valid up to some scale Λ. It can be extended to a field theory that satisfies the following requirements:

- its gauge group should contain $SU(3)_C \times SU(2)_L \times U(1)_Y$;
- all the SM degrees of freedom must be incorporated;
- at low energies (i.e. when $\Lambda \to \infty$), it should reduce to SM.

Assuming that such reduction proceeds via decoupling of New Physics (NP), the Appelquist-Carazzone theorem allows us to write such theory in the form:

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda} \sum_k C_k^{(5)} Q_k^{(5)} + \frac{1}{\Lambda^2} \sum_k C_k^{(6)} Q_k^{(6)} + \mathcal{O}\left(\frac{1}{\Lambda^3}\right).$$

Dimension-six operators

2-leptons

$$Q_{eW} = (\bar{l}_p \sigma^{\mu\nu} e_r)\tau^I \varphi W^I_{\mu\nu};$$
$$Q_{eB} = (\bar{l}_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}.$$
$$Q^{(1)}_{\varphi l} = (\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{l}_p \gamma^\mu l_r)$$
$$Q^{(3)}_{\varphi l} = (\varphi^\dagger i \overleftrightarrow{D}^I_\mu \varphi)(\bar{l}_p \tau^I \gamma^\mu l_r)$$
$$Q_{\varphi e} = (\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{e}_p \gamma^\mu e_r)$$
$$Q_{e\varphi} = (\varphi^\dagger \varphi)(\bar{l}_p e_r \varphi)$$

4-leptons

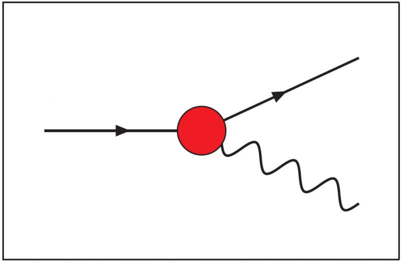
$$Q_{ll} = (\bar{l}_p \gamma_\mu l_r)(\bar{l}_s \gamma^\mu l_t)$$
$$Q_{ee} = (\bar{e}_p \gamma_\mu e_r)(\bar{e}_s \gamma^\mu e_t)$$
$$Q_{le} = (\bar{l}_p \gamma_\mu l_r)(\bar{e}_s \gamma^\mu e_t)$$

4-fermions

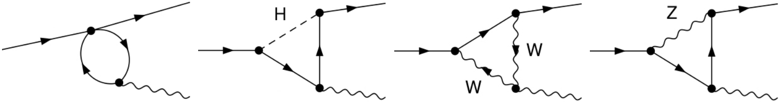
$$Q^{(1)}_{lq} = (\bar{l}_p \gamma_\mu l_r)(\bar{q}_s \gamma^\mu q_t)$$
$$Q^{(3)}_{lq} = (\bar{l}_p \gamma_\mu \tau^I l_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$$
$$Q_{eu} = (\bar{e}_p \gamma_\mu e_r)(\bar{u}_s \gamma^\mu u_t)$$
$$Q_{ed} = (\bar{e}_p \gamma_\mu e_r)(\bar{d}_s \gamma^\mu d_t)$$
$$Q_{lu} = (\bar{l}_p \gamma_\mu l_r)(\bar{u}_s \gamma^\mu u_t)$$
$$Q_{ld} = (\bar{l}_p \gamma_\mu l_r)(\bar{d}_s \gamma^\mu d_t)$$
$$Q_{qe} = (\bar{q}_p \gamma_\mu q_r)(\bar{e}_s \gamma^\mu e_t)$$
$$Q_{ledq} = (\bar{l}^j_p e_r)(\bar{d}_s q^j_t)$$
$$Q^{(1)}_{lequ} = (\bar{l}^j_p e_r)\varepsilon_{jk}(\bar{q}^k_s u_t)$$
$$Q^{(3)}_{lequ} = (\bar{l}^j_p \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar{q}^k_s \sigma^{\mu\nu} u_t)$$

Dimension-six operators: lepton current at one loop

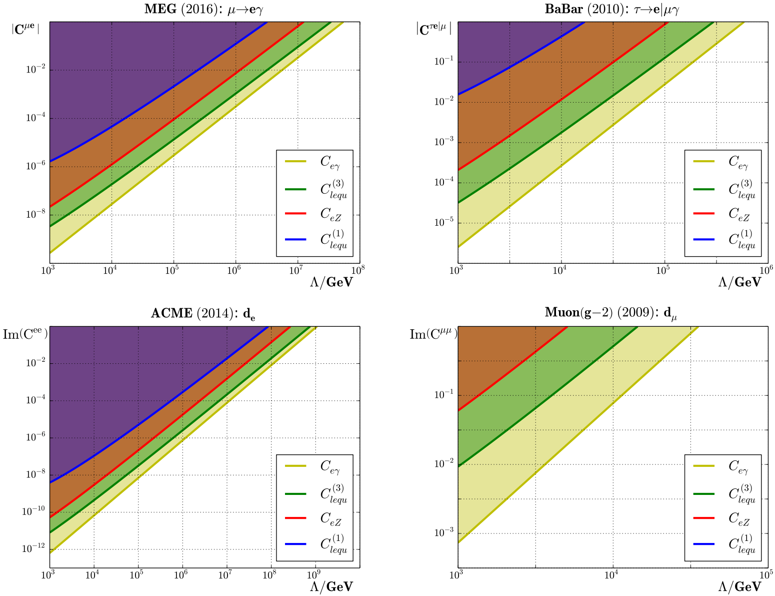
From a point-like interaction. . .



. . . to quantum fluctuations!



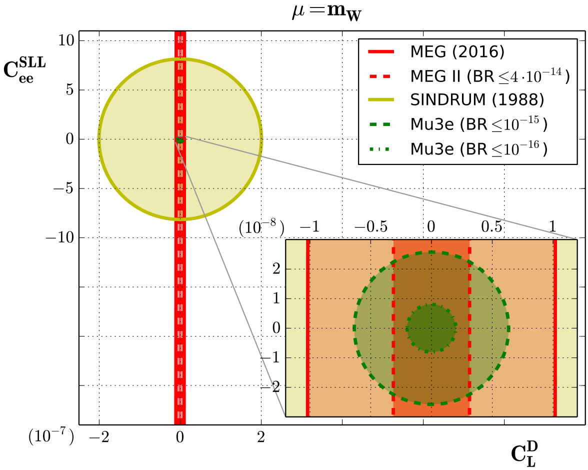
Experimental limits “reinterpreted” at the EW scale



Interplay between $\mu \to e\gamma$ and $\mu \to 3e$

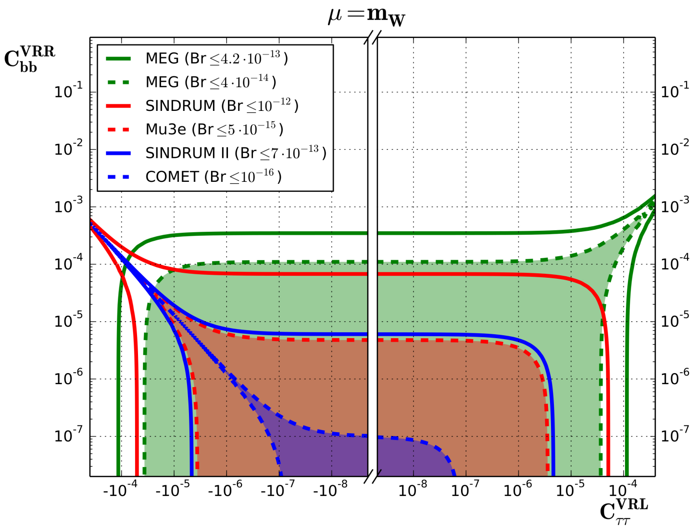
A. Crivellin, S. Davidson, GMP and A. Signer, arXiv:1611.03409 [hep-ph].

Below the EW scale, four-fermion vs dipole:



COMET/Mu2e money plot

A. Crivellin, S. Davidson, GMP and A. Signer, JHEP **1705** (2017) 117



The doubly Charged $SU(2)_L$-singlet scalar

Minimal model for neutrino mass generation

SM + 1 $SU(2)_L$-singlet doubly charged scalar: $S_R^{\pm\pm}$

It couples only with right-handed charged leptons:

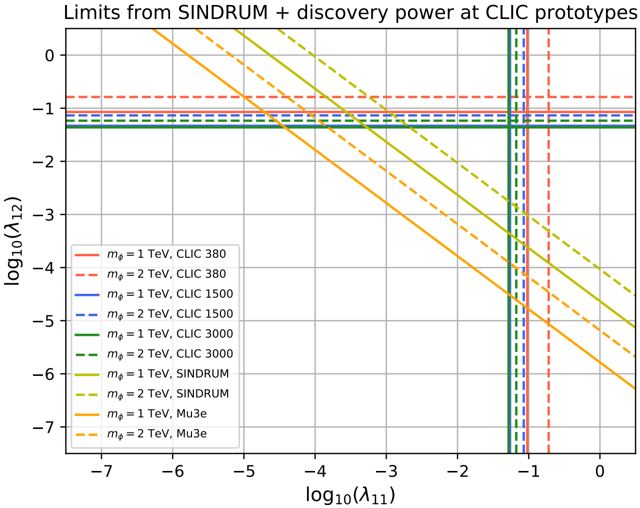
$$\begin{aligned}\Delta\mathcal{L} &= \left(D_\mu S^{++}\right)^\dagger \left(D^\mu S^{++}\right) + \left(\lambda_{ab}\,\overline{(\ell_R)^c_a}\ell_{Rb}\,S^{++} + \text{h.c.}\right)\\ &+ \lambda_2 \left(H^\dagger H\right)\left(S^{--}S^{++}\right) + \lambda_4 \left(S^{--}S^{++}\right)^2 + [\text{inv.}]\end{aligned}$$

λ_{ab} consists of 6 independent complex parameters.

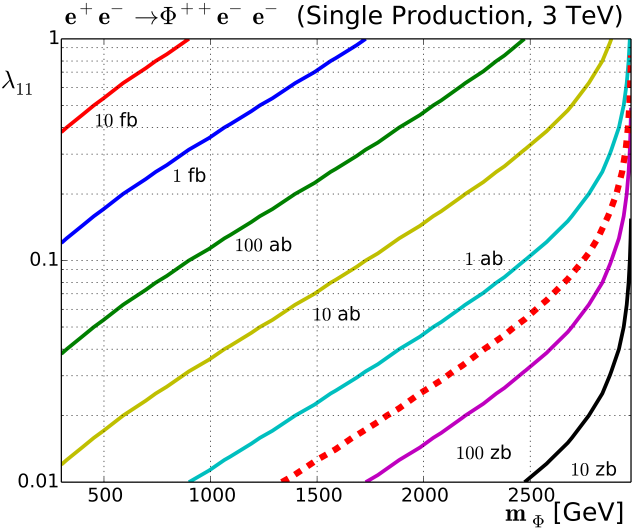
Lepton Flavour Violation

S. F. King, A. Merle and L. Panizzi, JHEP 1411 (2014) 124

Limits from low energy and discovery power of LC



Direct production at CLIC (3rd stage)



Conclusion

- √ CPV and LFV phenomena are forbidden in the minimal SM
  - Neutrino sector seems to ignore this fact, calling for something more than the minimal theoretical setup
  - Charged sector seems to take the job seriously
- √ If NP lives at very high energy, then consistent EFT techniques can be adopted to extract information of new physics at high scale from low-energy observables
- √ Precise background calculations are important to improve the experimental limits
- √ From limits on leptonic FV and EDM one can gain information on the parameter space of possible UV-complete BSM theories

Conclusion

- Doubly charged scalars arise in many BSM models, in triplets or singlets under $SU(2)_L$, often in connection with the neutrino masses;
- LFV low energy processes set strong limits on combination of the DCS couplings to leptons;
- future e^+e^- colliders can provide complementary bounds;
- due to the production of the DCS in the t-channel, e^+e^- colliders can be sensitive to mass scales of several TeV;
- further investigations of the DCS phenomenology are ongoing and the results will be published soon.